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Collisional Emittance Growth in The Particle Simulation of Focused Beam Transport

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By varying the number of particles used in the simulation, it is shown that numerical collisions result in a non-physical emittance growth which is proportional to the collision frequency. It is also shown that enough particles can be used so that the systems behavior is independent of their number.

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COLLISIONAL EMITTANCE GROWTH IN THE PARTICLE SIMULATION OF FOCUSED BEAM TRANSPORT

Recent work on space charge limited transport[1,2] has revealed the presence of instabilities in a beam with a Kapchinskij–Vladimirskij[3] (K-V) distribution. Computer simulations have shown that, in many cases, these instabilities saturate with relatively little emittance growth[4]. Because of the importance of space charge limited transport to the heavy ion fusion program, several simulation efforts have been undertaken[5,6]. Since it is impractical to calculate the orbits of a number of particles comparable to the actual number in a physical particle beam, it is the purpose of this report to discuss the effects due to using a much smaller number in the computer simulation.

In an ensemble of charged particles a force is exerted on each particle by all the others in the ensemble. It is therefore possible to sum up the forces on each particle due to all the others and use this force to calculate the particle acceleration and then integrate to find its orbit. The number of operations in the approach increases as the square of the number of particles, n^2.

On the other hand, it is possible to exploit the long range nature of the coulomb interaction to design an algorithm which instead of scaling as n^2 scales as n. When the number of particles in a Debye sphere is much greater than unity, an ensemble of charged particles interacts not through the nearest neighbor forces but through the collective electric fields. Numerical algorithms extensively employed in plasma physics[7] find these electric fields by accumulating the individual particle charges to determine the charge density on a grid, and then solving

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Poisson's equation to find the corresponding electric field on this grid. These grid fields are then used to move the particles.

A previous report[8] dealt with the effects of varying various numerical parameters in this approach. Its emphasis was however, on the effects after a short time and the number of particles was chosen large enough so that only minimal effects were seen by factor of two changes in their number. Since the binary interaction approach, though impractical for large number of particles, can be more efficient for a small number of particles, it is important to determine how many particles are actually needed and perhaps, just as important, whether it is possible to tell when not enough are being employed.

Figure 1 is a plot of the product of the rms values of x and P_x and the same product for y and P_y of a matched K-V distribution in a thin lens quadrupole system with a 90° phase advance. The space charge strength is sufficient to depress the tune to 30°. The initial conditions are found by iterating so that the variation in x and y of the bounding ellipse is minimized over the first pair of lenses. This seems to result in a favoring of the x dimension so that the rms emittance growth in the x dimension is less than in the y direction. It is important to note that both emittances stop evolving after about 40 lens pairs and, except for some fluctuations, are essentially constant.

The problem of collisions in particle in cell codes has been investigated in detail in connection with plasma simulations[9]. In this run 16,000 particles were employed on a 128 × 128 grid. If the velocity corresponding to the maximum x-velocity of the initial ellipse and the initial plasma frequency ω_p are used, the parameter

$$\lambda = \frac{V_{x\max}}{\omega_p} \tag{1}$$

can be defined as a characteristic length similar in sense to the debye length. The number of particles in an area λ^2 would then provide an estimate of the system collision time. In this particular simulation, the beam area is approximately $130\lambda^2$. The plasma time is $2\pi/\omega_p \simeq 3$ doublets. The collision time, τ_c, is therefore approximately

$$\tau_c \approx \frac{16}{\pi\omega_p}\,\frac{N}{130} \approx \frac{N}{50} \text{ doublets} \qquad (2)$$

For 16000 particles this is about 320 doublets.

A close look at the curves in Fig. 1 shows that both the x and y rms emittances do appear to have a very slow secular growth time on the order of several hundred doublets. By estimating the slope for this curve and normalizing to the initial emittance $\frac{1}{\epsilon_o}\left(\frac{d\epsilon}{dT}\right) \simeq 10^{-3}$/doublets or $\tau \approx 10^3$. This slow secular growth, the lack of coupling between the x and y rms emittances and the approximate calculated value of collision frequency all point to the collisionless nature of this simulation. In fact, since the distribution function is rapidly changing as the particles move between lenses, and the final distribution is far from a K-V distribution, only an order of magnitude estimate of the collision time is appropriate. By decreasing the number of particles it should, however, become possible to see a change in behavior when the run time becomes of the order of several collision times. An even more radical change should occur when the collision time becomes comparable to the growth time of the instability.

Figure 2 is a plot of the same simulation run with 1024 particles. This would predict a collision time of about 25 doublets. Note that the qualitative behavior of the emittance, i.e. the initial constancy, rapid growth, and leveling off, is the same. The saturation level is also about the same as in Fig. 1. However, some rounding of the knee of the curves and a greater secular growth in the emittance are apparent.

A further decrease of a factor of two to 512 particles has a more radical effect. The features of Figs. 1 and 2 are sharply washed out. The calculated collision time for this run would be about 13 doublets.

Figures 3 and 4 show similar curves for 256 and 128 particles respectively. Little evidence of the same qualitative behavior as in the collisionless regime is still evident.

Figure 5 is a plot on log-log paper of the slope $\frac{d(\epsilon/\epsilon_o)}{d\tau}$ vs. N, where τ is the period of the lens doublet, and N is the number of particles. Figure 4 has a break in the slope at about $t = 60$ doublets, so both slopes are plotted for $N = 128$. The straight line is a $-45°$ line drawn assuming the rate of growth in emittance is proportional to the inverse of the number of particles so that $n \frac{d(\epsilon/\epsilon_o)}{d\tau} =$ constant. The line drawn corresponds to a constant of 5. This compares to a proportionality of about 50 obtained for the ratio N/τ_c in Eq. (2) where τ_c is the collision time found previously. It should be noted that Figure 5 indicates that the slope of the emittance in Figure 1, which is the run with 16000 particles, can not be explained by numerical collisions.

These runs have dramatically illustrated the effects an insufficient number of particles can have on the behavior of the beam system being simulated. Furthermore it appears necessary to have a collision time much greater than the growth time of the instability. In the absence of a well defined theory, simulations should either have enough particles so the collisionless behavior is not open to doubt or several runs must be made in order to test the numerics.

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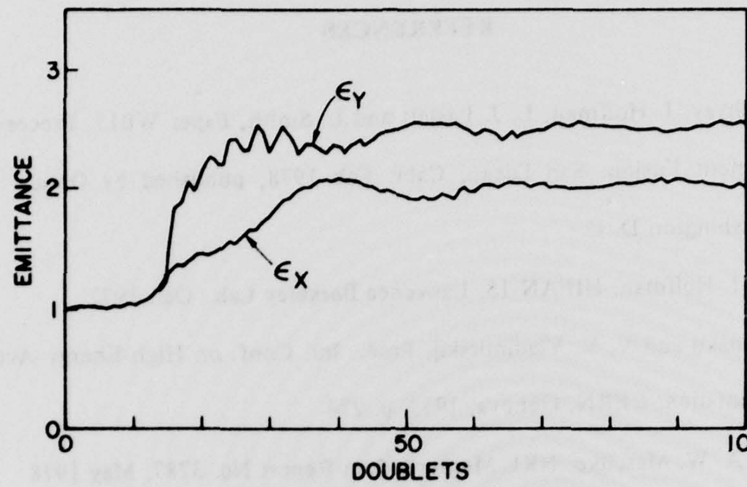

Fig. 1 – Time evolution of the *x* and *y* rms emittances of a [illegible] particle K-V distribution as it propagates through a thin lens system with 90° phase adva[illegible]ced to 30° by space charge.

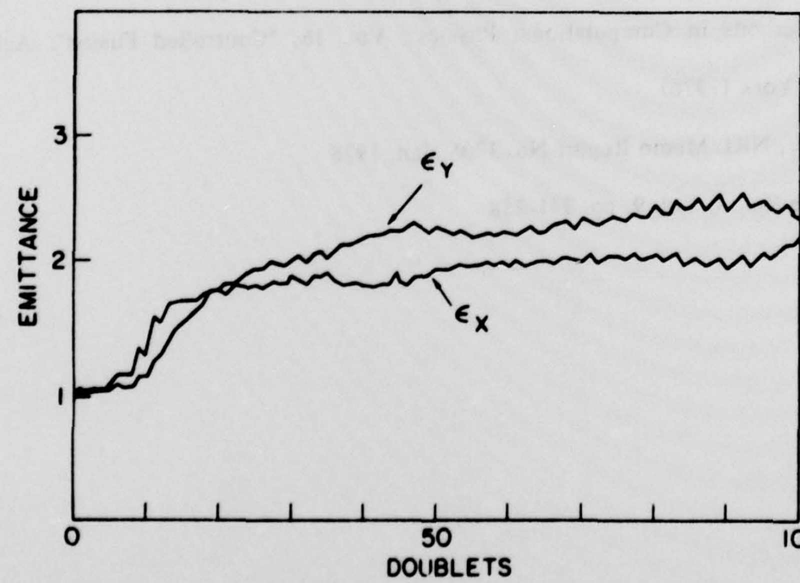

Fig. 2 – Time evolution of the same system as Fig. 1 with 1024 particles showing only minor differences in the qualitative behavior.

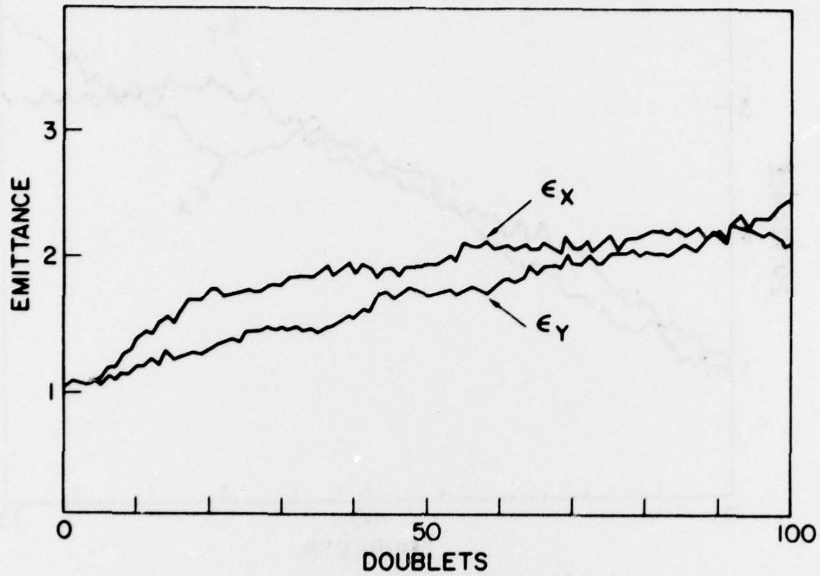

Fig. 3 – Time evolution of the same system as Fig. 1 with 512 particles. Major differences are now visible in the behavior.

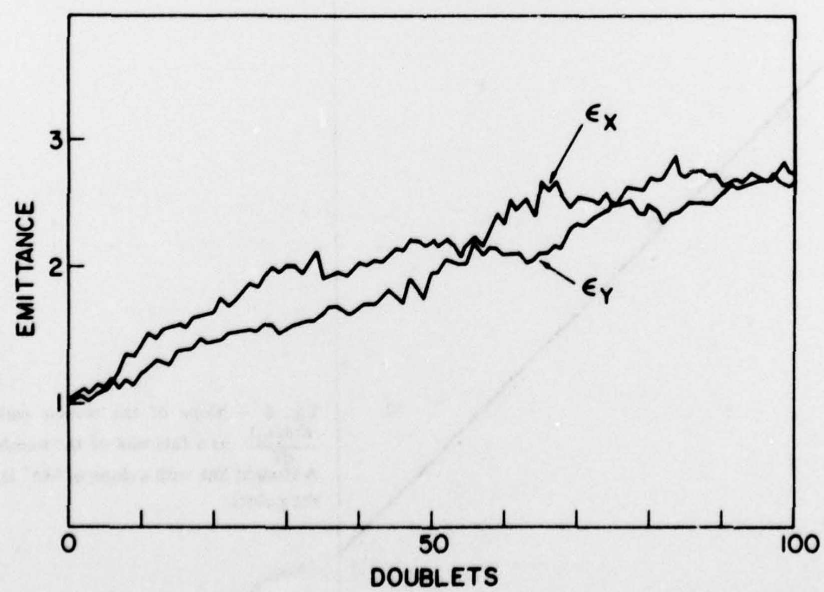

Fig. 4 – Time evolution of the system with 256 particles showing increased collisional growth rate in the emittance and further disruption of the ordered evolution of the regions of instability and saturation in *Fig. 1*.

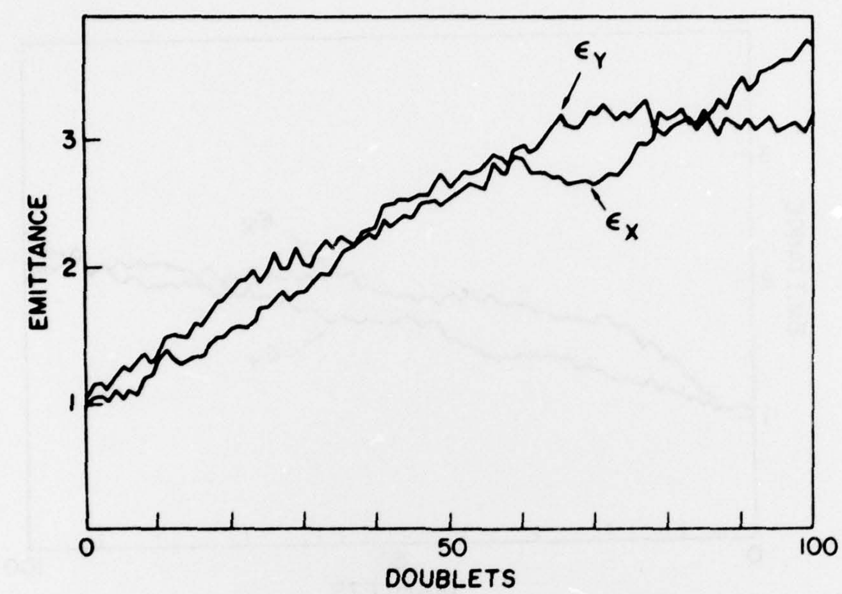

Fig. 5 – Time evolution of the system with 128 particles showing even stronger collisional effects.

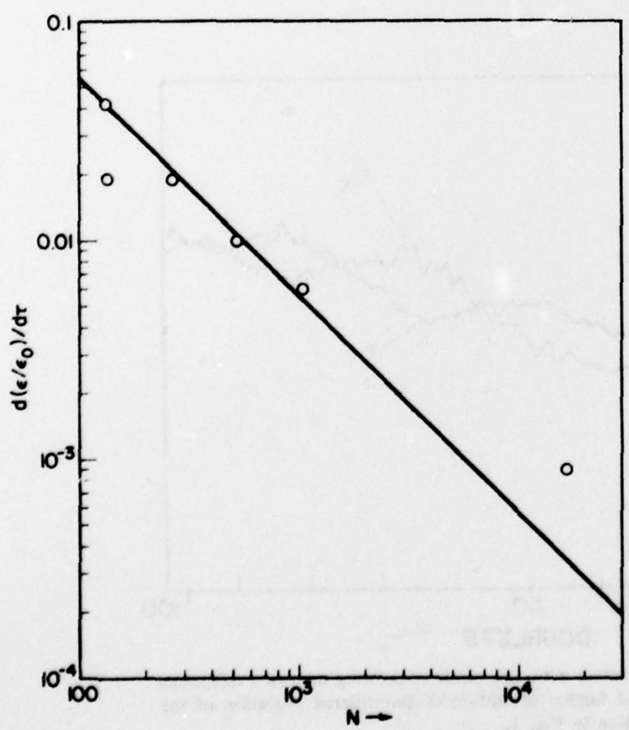

Fig. 6 – Slope of the secular emittance growth $\frac{d(\epsilon/\epsilon_0)}{d\tau}$ as a function of the number of particles. A straight line with a slope of -45° is fitted through the points.